ASCA observations of the nearby galaxies Dwingeloo 1 and Maffei 1

C. S. Reynolds[1]⋆, A. J. Loan[1], A. C. Fabian[1], K. Makishima[2], W. N. Brandt[1] and T. Mizuno[2]

[1] *Institute of Astronomy, Madingley Road, Cambridge CB3 OHA*
[2] *Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan*

ABSTRACT

We present *ASCA* observations of the nearby galaxies Dwingeloo 1 (Dw1) and Maffei 1 (Mf1). X-ray sources are clearly detected within 3 arcminutes of the optical nuclei of both galaxies. Despite the low Galactic latitude of these fields ($|b| < 1°$) we conclude, on probability and spectral grounds, that the detected sources are intrinsic to these galaxies rather than foreground or background interlopers. The Dw1 source, designated Dw1-X1, is interpreted as being either a hyper-luminous X-ray binary (with a 0.5–10 keV luminosity of more than 10^{39} erg s^{-1}) or an X-ray bright supernova. The Mf1 emission is hard and extended, suggesting that it originates from a population of X-ray binaries. Prompted by the Dw1-X1 results, we discuss the nature of hyper-luminous X-ray binary systems. Such sources are commonly seen in nearby galaxies with a frequency of approximately one per galaxy. We present a possible connection between these luminous systems and Galactic superluminal sources.

Key words: galaxies: individual: Dwingeloo 1 - galaxies: individual: Maffei 1 - X-rays: galaxies - X-rays: stars - accretion

1 INTRODUCTION

It is now becoming apparent that 'normal' galaxies host a variety of exotic objects (Makishima 1994; Fabbiano 1995). Although the Milky Way and the Andromeda Galaxy (M31) are unusually quiescent in the X-ray band, recent sensitive studies of other nearby spiral galaxies have revealed a number of sources of high-energy radiation. These are interpreted variously as unusually powerful accreting stellar sources, supernova remnants, superbubbles of hot gas associated with starbursts, or active galactic nuclei (AGN) with unusually low X-ray luminosity. Examples of low-luminosity AGN (LLAGN) include M106 (Makishima et al. 1994), M81 (Petre et al. 1993; Ishisaki et al. 1996), M51 (Ehle, Pietsch & Beck 1995), and IC342 (Fabbiano & Trinchieri 1987; Bregman, Cox & Tomisaka 1993; Makishima 1994; Okada et al. 1994). Many of these galaxies, as well as NGC1313 (Petre et al. 1994; Colbert et al. 1995), M82 (Stocke, Wurtz & Kühr 1991) and others (see Table 9.2 of Fabbiano 1995), have variable non-nuclear pointlike sources with 2–10 keV isotropic luminosities up to $\sim 10^{40}$ erg s^{-1}. If these sources are X-ray binaries (XRB), the observed luminosity requires either the accretion to be significantly above the Eddington limit or

⋆ Present address: JILA, University of Colorado, Boulder, CO 80309-0440, USA.

onto an implausibly massive black hole (with $M \gtrsim 100\,M_\odot$: see discussion in Section 2.3.2), or for the emission to be highly anisotropic. In any case, this class of XRB represents an unusual departure from most Galactic XRB. With the sensitivity of *ASCA*, a typical 40 000 s observation could detect (at 5σ confidence) a 10^{40} erg s^{-1} point source at distances $\lesssim 30$ Mpc. Any detailed study would require a flux ~ 2 orders of magnitude larger than this detection threshold. Thus, such sources can only be studied in local galaxies (with distances $\lesssim 3$ Mpc).

In 1994 August the Dwingeloo Obscured Galaxy Survey detected the 21 cm emission from a new nearby barred spiral galaxy – now known as Dwingeloo 1 (Dw1; Kraan-Korteweg et al. 1994). Tully-Fisher distance estimates place Dw1 at ~ 3 Mpc (Loan et al. 1996). Optical photometry implies that Dw1 has an unusually blue core, suggesting possible nuclear activity. X-ray observations of Dw1 present us with the ideal opportunity to study the high-energy emission from a previously unknown, major, nearby spiral galaxy.

Maffei 1 (Mf1; Maffei 1968) is the nearest major elliptical galaxy, at a distance of ~ 3 Mpc (van den Bergh 1994). An observation of Mf1 with the imaging proportional counter (IPC) of the *Einstein* observatory found a weak X-ray source with an observed 0.8–3.5 keV flux of $(3.3\pm0.5)\times10^{-13}$ erg cm^{-2} s^{-1}, identifiable with Mf1 (Markert & Donahue 1985). The alignment of several other sources

Table 1. Basic parameters for the *ASCA* observations of Dw1 and Mf1. The table shows a) the good SIS and GIS times (given the selection criteria discussed in the text), b) total number of source and background photons in the SIS and GIS source regions, c) the SIS and GIS count rates of the detected sources (background subtracted), d) observed (i.e. absorbed) 0.5–10 keV and 2–10 keV fluxes of the sources and e) intrinsic (i.e. absorption corrected) 0.5–10 keV and 2–10 keV luminosities of the sources assuming them to lie at a distance of 3 Mpc (the assumed distance of Dw1 and Mf1). The fluxes and luminosities were calculated using the best fit power-law model with cold absorption, although the values are fairly insensitive to the exact model used.

	Dw1	Mf1
Good SIS time (s)	37462	35000
Good GIS time (s)	41508	39477
SIS total counts	472	1206
GIS total counts	1238	1957
SIS count rate $(\mathrm{cts\,s^{-1}})$	8.7×10^{-3}	2.4×10^{-2}
GIS count rate $(\mathrm{cts\,s^{-1}})$	1.1×10^{-2}	2.4×10^{-2}
$F_{2-10\,\mathrm{keV}}(10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}})$	6.7	12
$F_{0.5-10\,\mathrm{keV}}(10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}})$	7.5	15
$L_{2-10\,\mathrm{keV}}(10^{38}\,\mathrm{erg\,s^{-1}})$	8.1	14
$L_{0.5-10\,\mathrm{keV}}(10^{38}\,\mathrm{erg\,s^{-1}})$	14	25

Figure 1. *I*-band image of Dw1 taken with the INT. The optical nucleus of Dw1 lies slightly to the right of the frame centre. Overlaid are logarithmically spaced contours of the GIS2 full band image. Dw1-X1 is clearly displaced ~ 3 arcmin north-east of the optical nucleus of Dw1. Contours correspond to 0.89, 0.71, 0.56, 0.45 of the peak X-ray surface brightness. For comparison, the average background level is ~ 15 per cent of the peak surface brightness with maximum fluctuations up to ~ 30 per cent of the peak surface brightness.

in the field with possible optical counterparts strongly suggested that the astrometry was correct and that the identification with Mf1 was secure. The observation hinted that this source was spatially extended, although the possibility of foreground contamination and blending of some nearby sources prevented a definitive statement from being made. Markert & Donahue concluded that the X-ray emission from Mf1 is from either a LLAGN, a centrally condensed population of XRB, or hot interstellar medium (ISM).

Both Dw1 and Mf1 lie at low Galactic latitude ($b = -0.1°$ and $b = -0.6°$ respectively). H I measurements and extinction estimates yield neutral hydrogen column densities towards Dw1 and Mf1 of $7 \times 10^{21}\,\mathrm{cm^{-2}}$ (Burton et al. 1996) and $8 \times 10^{21}\,\mathrm{cm^{-2}}$ (Buta & McCall 1983) respectively. This high level of absorption and extinction severely hampers studies of these galaxies at optical wavelengths. Infrared studies are difficult due to confusion caused by foreground Galactic stars. However, observations in the hard X-ray band ($\gtrsim 2\,\mathrm{keV}$) are little affected by the low Galactic latitude.

Here we present *ASCA* observations of Dw1 and Mf1. The range of energies observable by the detectors on *ASCA*, 0.5–10 keV, lies mostly above the threshold at which Galactic absorption is important. Coupled with the high sensitivity, superior spectral resolution and imaging ability of *ASCA*, these observations constitute the most detailed high-energy study to date of these two nearby galaxies. Sections 2 and 3 present our analysis of the data for Dw1 and Mf1 respectively. We clearly detect emission within a few arcmins of the optical nucleus of each galaxy (1 arcmin corresponds to 1 kpc at the distance of Dw1 and Mf1). We discuss physical interpretations for these emissions. The Dw1 source, designated Dw1-X1, is interpreted as being either a hyper-luminous XRB or a X-ray bright supernova. The Mf1 emission is hard and extended, suggesting that it originates from a population of X-ray binaries. Prompted by our Dw1-X1 results, we discuss the nature of hyper-luminous X-ray binary systems. Such sources are commonly seen in nearby galaxies
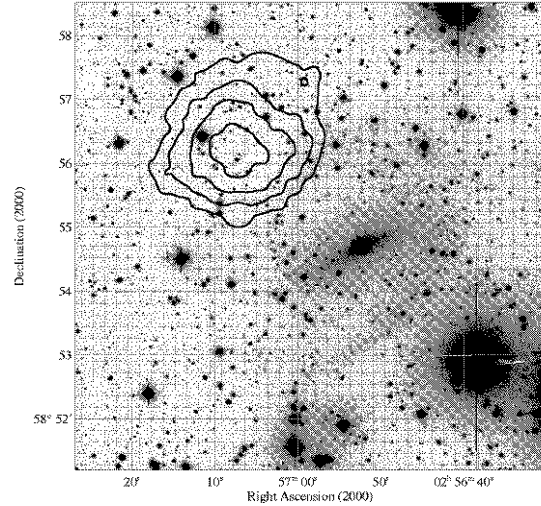
with a frequency of approximately one per galaxy (Fabbiano 1995). In Section 4, we present a possible connection between these luminous systems and Galactic superluminal sources. Section 5 presents our conclusions.

2   DWINGELOO 1

On 1995 September 14/15, *ASCA* observed Dw1 for approximately one day. We used both Solid-state Imaging Spectrometers (SIS) in 1-CCD mode (chip 1 for SIS0 and chip 3 for SIS1). Further details of the *ASCA* instrumentation can be found in Tanaka, Inoue & Holt (1994). Data from the SIS were cleaned in order to remove the effects of hot and flickering pixels and subjected to the following data-selection criteria: i) the satellite should not be in the South Atlantic Anomaly (SAA), ii) the object should be at least 5° above the Earth's limb, iii) the object should be at least 25° above the day-time Earth limb and iv) the local geomagnetic cut-off rigidity (COR) should be greater than 6 GeV/c. Data from the Gas Imaging Spectrometers (GIS) were cleaned to remove the particle background and subjected to the follow-
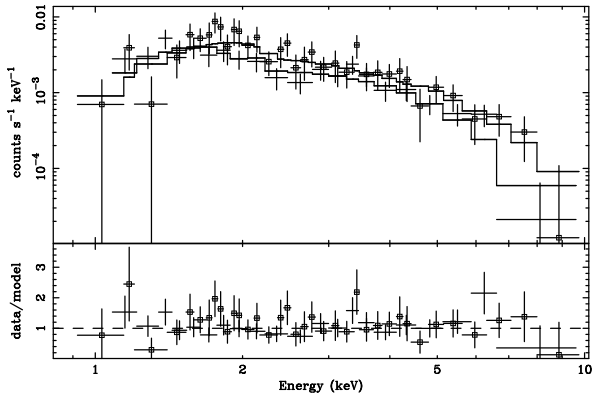
Figure 2. SIS0 (plain crosses) and GIS2 (crosses with open circles) spectra of Dw1-X1. Although all four instruments were used for spectral fitting, only these two are displayed in order to maintain clarity. The top panel shows the data fitted with the best fit absorbed power-law model of Section 2.2 (shown by solid lines). The bottom panel illustrates the ratio of data to this best fit model.

ing data-selection criteria: i) the satellite should not be in the SAA, ii) the object should be at least 7° above the Earth's limb and iii) the COR should be greater than 7 GeV/c. SIS and GIS data that satisfy these criteria shall be referred to as 'good' data. Table 1 gives the 'good' integration times for the SIS and GIS.

2.1 Image analysis

Images were extracted from the good data for each of the four instruments. We clearly detected a bright point-like source (i.e. with a surface brightness profile consistent with that of the point spread function in both the SIS and GIS instruments). Hereafter this source will be referred to as Dw1-X1. Figure 1 shows contours of this X-ray image overlaid on an *I*-band image from the Isaac Newton Telescope (INT) of this region (Loan et al. 1996). Despite the numerous Galactic stars, Dw1 can be clearly seen at the centre of Fig. 1 displaying a strong bar and faint spiral arms (extending outwards in a clockwise direction). As reported in Table 1, the 2–10 keV flux of this source is 6.7×10^{-13} erg cm^{-2} s^{-1} (assuming the best fit power-law spectrum of Section 2.2). Dw1-X1 is displaced ~ 3 arcmins to the north-east of the optical nucleus of Dw1. A recent study shows that the pointing accuracy of *ASCA* has a random positional offset following a Poisson probability distribution with mean of ~ 0.4 arcmin (Gotthelf 1996). Thus Dw1-X1 is extremely unlikely to be associated with the optical nucleus of Dw1 (with a probability of $\sim 5 \times 10^{-4}$). We note that the H I disk of Dw1 has a diameter $\sim 12'$ and so easily encompasses the position of Dw1-X1 (Burton et al. 1996). No nuclear emission is seen from Dw1: the corresponding limit on the 2–10 keV flux of the nucleus is $F_{2-10} \lesssim 1 \times 10^{-13}$ erg cm^{-2} s^{-1}.

2.2 Spectral and temporal analysis of Dw1-X1

Light curves and spectra were extracted for the counts contained within a circular region centred on Dw1-X1 with a radius of 4 arcmin. Background spectra were also extracted from source free regions of the same field of view for each instrument. For the purposes of spectroscopy, only 0.6–10 keV SIS data and 0.9–10 keV GIS data were used. The spectra were binned so as to have at least 20 photons per energy bin: this requirement ensures that χ^2 statistics apply. Table 1 shows the count rates, 2–10 keV flux and the 2–10 keV luminosity if we choose to place it at the distance of Dw1. The light curves of all instruments are consistent with the source being constant (χ^2/dof=21/33 for the SIS0 light curve) although variability would have to be dramatic in order to be detectable in a source with such a low count rate. We estimate that a variation by a factor of two sustained over $\gtrsim 2000$ s (corresponding to the good data period of one or more *ASCA* orbits) would be marginally detectable at the 3-σ level.

Spectral fitting was performed using background subtracted data from all four *ASCA* instruments simultaneously. We initially considered four spectral models: blackbody emission, thermal bremsstrahlung, Raymond-Smith thermal plasma emission (including line emission) and a power-law. The effects of cold absorption were included, leaving the column density as a free parameter. There are known small discrepancies (at the 10–20 per cent level) between the normalisation of each of the four instruments. Thus, the best fit spectrum was allowed to have independent normalisations in each instrument. The results of these fits are shown in Table 2.

The bremsstrahlung, Raymond-Smith and power-law models all describe the data equally well. The black-body model is a poorer description of the data and results in an unmodelled hard tail to the spectrum. Adding a second black-body component leads to a significant improvement in the goodness of fit ($\Delta\chi^2 = 20$ for extra 2 parameters), as can be seen from Table 2. Note that adding a power-law, bremsstrahlung or Raymond-Smith component to the single black-body model in an attempt to model the hard tail leads to that component completely dominating the spectrum (i.e. the models essentially become one of those listed in Table 2). Figure 2 shows the best-fitting (folded) power-law model compared to the data together with a ratio plot of the data divided by the model.

A wide variety of astrophysical X-ray sources display iron Kα line emission (with energies ranging from 6.4–6.9 keV depending on the dominant ionization state of iron). Thus, although the simple models presented above are completely adequate descriptions of the *ASCA* spectrum of Dw1-X1, it is instructive to find an upper limit to the equivalent width (EW) of any iron line emission. A narrow line at 6.4 keV (representing cold iron) was added to both the thermal and power-law models above. The addition of the iron line produced no improvement in the goodness of fit: the best fit EW is zero. For all of the above models, an upper limit can be set of EW<600 eV (at the 90 per cent confidence level for one interesting parameter, $\Delta\chi^2 = 2.7$).

2.3 The physical nature of Dw1-X1

Table 2. Spectral fitting results for Dw1-X1. Abbreviations are as follows: bb=black-body; brems=thermal bremsstrahlung; rs=Raymond-Smith thermal plasma code (Raymond & Smith 1977); pl=power-law; NH=cold absorbing column. All errors are quoted at the 90 per cent confidence level for one interesting parameter, $\Delta\chi^2 = 2.7$.

Model	parameter	value	χ^2/dof
bb+NH	temperature	$kT = 1.03^{+0.09}_{-0.08}$ keV	137/138
	cold absorbing column	$N_{\mathrm{H}} < 3 \times 10^{21}$ cm^{-2}	
bb+bb+NH	temperatures	$kT_1 = 0.49^{+0.18}_{-0.15}$ keV	117/136
		$kT_2 = 1.5^{+0.5}_{-0.3}$ keV	
	rel. norms at 1 keV	$A_1/A_2 = 0.64$	
	cold absorbing column	$N_{\mathrm{H}} = (1.0 \pm 0.6) \times 10^{22}$ cm^{-2}	
brems+NH	temperature	$kT = 6.6^{+4.0}_{-2.1}$ keV	120/138
	cold absorbing column	$N_{\mathrm{H}} = (1.1 \pm 0.3) \times 10^{22}$ cm^{-2}	
rs+NH	temperature	$kT = 5.9^{+4.3}_{-1.8}$ keV	120/137
	abundance	$Z < 0.54$	
	cold absorbing column	$N_{\mathrm{H}} = (1.1 \pm 0.3) \times 10^{22}$ cm^{-2}	
pl+NH	photon index	$\Gamma = 2.0 \pm 0.3$	119/138
	cold absorbing column	$N_{\mathrm{H}} = 1.4^{+0.4}_{-0.3} \times 10^{22}$ cm^{-2}	

2.3.1 *Locating the source along our line of sight*

Any discussion of the nature of Dw1-X1 must begin by considering its location along our line of sight. To demonstrate that this source is intrinsic to Dw1, we must exclude the possibilities of it being a foreground Galactic source (e.g. a flare star or XRB) or a background AGN.

The spectral results of Section 2.2 clearly show the effects of soft X-ray absorption by cold material. For the power-law, bremsstrahlung and Raymond-Smith models presented above, the column density inferred from X-ray absorption exceeds the Galactic column inferred from H I and extinction measurements ($N_{\mathrm{H}} \approx 7 \times 10^{21}$ cm^{-2}). The double black-body model admits a rather lower cold column due to the intrinsic low-energy turnover of the model. However, even within this model, the 90 per cent lower limit to the cold column is $N_{\mathrm{H}} > 4 \times 10^{21}$ cm^{-2} and the preferred column is $N_{\mathrm{H}} = 1 \times 10^{22}$ cm^{-2}.

The fact that the spectrum of Dw1-X1 seems to suffer absorption by at least a significant fraction of the Galactic suggests that Dw1-X1 lies no closer than the far side of our Galactic disk and is probably extragalactic. If the power-law or optically-thin thermal models are a correct description of the spectrum, there is also evidence for intrinsic absorption in the source (above that expected from the Galaxy). However, self-absorption of the 21-cm line can lead to H I measurements underestimating the true H I column density when it is large. This may allow the Galactic H I measurements to be consistent with the *ASCA* measurements. We note that the above argument is based on our one-component spectral fits.

We can also argue against Dw1-X1 being of Galactic origin on probabilistic grounds. The question is precisely phrased as follows: what is the probability of finding a Galactic X-ray source with at least the flux of the *ASCA* Dw1 source within 3 arcmin of the optical nucleus of Dw1? The *Einstein* Galactic Plane Survey (Hertz & Grindlay 1984) find a total of ~ 0.4 sources per square degree with a 0.1–4.5 keV flux above that of Dw1-X1 (4×10^{-13} erg cm^{-2} s^{-1}). Most of these are Galactic sources. Inspection of the *ROSAT* All Sky Survey (Voges et al. 1996) shows Dw1 to lie in a representative region of the Galactic plane. Given this the probability of Dw1-X1 being a foreground source is $\sim 3 \times 10^{-3}$. This probability is an overestimate since it does not take into account the spectral information discussed in the previous paragraph (which implies it must lie at least on the far side of the Galactic disk). Thus, we discount this possibility.

Similarly, we use probabilistic arguments to address whether this source can be a background AGN. Again, the question is precisely phrased as follows: what is the probability of finding an AGN with at least the flux of the Dw1 source within 3 arcmin of the optical nucleus of Dw1? The Deep *ROSAT* Survey of Boyle et al. (1994) provides the most pertinent data with which to answer this question. Using the best fit power-law model of Section 2.2, the unabsorbed 0.5–2 keV flux of the Dw1 source is 5.4×10^{-13} erg cm^{-2} s^{-1}. The Deep *ROSAT* Survey suggests ~ 0.5 AGN per square degree of this flux level or greater. Assuming this to be representative of the AGN background in the Dw1 region implies that the probability of the Dw1 *ASCA* source being a background AGN is only $\sim 4 \times 10^{-3}$. Thus, we also reject this possibility on probabilistic grounds.

We conclude that the positional coincidence of Dw1-X1 with Dw1, coupled with an X-ray spectrum that has most likely suffered Galactic absorption, presents a strong argument for the source to be intrinsic to Dw1. Table 1 gives the unabsorbed luminosities of the source in the 0.5–10 keV and 2–10 keV bands if it is placed at the distance of Dw1 (~ 3 Mpc). The 3 arcmin offset from the optical nucleus implies Dw1-X1 lies a distance of 2.6 kpc from the centre of Dw1. Although Dw1-X1 appears to lie beyond the optical extent of Dw1 (see Fig. 1), this is a consequence of the high optical extinction along this line of sight: the observed offset is completely consistent with Dw1-X1 lying within Dw1. Note for comparison that the H I extent of Dw1 is ~ 12 arcmins corresponding to a diameter of 10 kpc.

2.3.2   The nature of the source

The location of Dw1-X1 within the host galaxy suggests that it is a stellar phenomenon. Emission from a population of ordinary stars would produce a much fainter and more diffuse emission than is observed. Thus, we are led to consider stellar exotica such as superbubble regions (associated with starbursts), supernova remnants and XRBs.

Large regions of hot gas associated with starburst activity, so-called superbubbles, have probably been detected in several nearby galaxies (see NGC 5408: Fabian & Ward 1993; NGC 1672: Brandt, Halpern & Iwasawa 1996). The known examples tend to have soft optically-thin thermal X-ray spectra (with $kT \sim 0.5\,\mathrm{keV}$). Such emission is much softer than that of Dw1-X1. Thus we confidently reject the hypothesis that Dw1-X1 is a superbubble.

A young supernova remnant that is expanding in a dense circumstellar medium is a possibility for the observed emission (see Schlegel 1996 and detection of SN1988Z in X-rays by Fabian & Terlevich 1996). Indeed, the spectrum and luminosity of Dw1-X1 are similar to that of the X-ray bright supernova SN1978K seen in NGC1313 (Ryder et al. 1993; Petre et al. 1994; Colbert et al. 1995). Since Dw1 has only been recently discovered, little direct information exists on the supernova history of this galaxy. However, we can argue against the supernova hypothesis for Dw1-X1 on the basis of radio observations. X-ray bright supernovae are known to be strong sources of continuum radio emission, e.g. SN1986J (Weiler, Panagia & Sramek 1990) and SN1988Z (Van Dyk et al. 1993). Although very dependent on supernova age and environment, we would expect any such supernova in Dw1 to have a radio flux of $\sim 1\,\mathrm{Jy}$ at $1.4\,\mathrm{GHz}$ (corresponding to $\nu L_\nu \approx 10^{37}\,\mathrm{erg\,s^{-1}}$ at $1.4\,\mathrm{GHz}$, assuming a distance of $3\,\mathrm{Mpc}$). Published observations provide upper limits on the radio continuum luminosity of Dw1-X1 of $50\,\mathrm{mJy}$ at $408\,\mathrm{MHz}$ (Green 1989) and $0.4\,\mathrm{mJy}$ at $1.420\,\mathrm{GHz}$ (Burton et al. 1996).

Given the ambiguities mentioned above, the present observations cannot rule out the possibility that Dw1-X1 is a young supernova remnant. However, such X-ray bright supernovae are rare phenomena. Moreover, many other well studied galaxies display luminous non-nuclear sources which do not correspond with the position of any known supernovae. Several of these luminous non-nuclear sources are also known to be variable: the luminous off-nuclear source associated with IC342 shows clear short term variability (Makishima 1994; Okada et al. 1994). For these reasons, such sources are identified as accreting compact objects.

The absorption corrected 0.5–$10\,\mathrm{keV}$ luminosity of Dw1-X1 (assuming a power-law for for the spectrum) is $1.4 \times 10^{39}\,\mathrm{erg\,s^{-1}}$. Depending on the details of the source, there is likely to be significant emission outside of the *ASCA* band. Including emission from all other wavebands, the bolometric luminosity of this source is probably as high as $\sim 3 \times 10^{39}\,\mathrm{erg\,s^{-1}}$. This luminosity exceeds any persistent Galactic XRB by a factor of a few. Indeed, it corresponds to the Eddington limit for a $20\,\mathrm{M_\odot}$ compact object. This is in excess of the mass limit for a neutron star ($\sim 3\,\mathrm{M_\odot}$) or a black hole formed by the collapse of a normal massive star (thought to be 10–15 $\mathrm{M_\odot}$: e.g. see Timmes, Woosley & Weaver 1996).

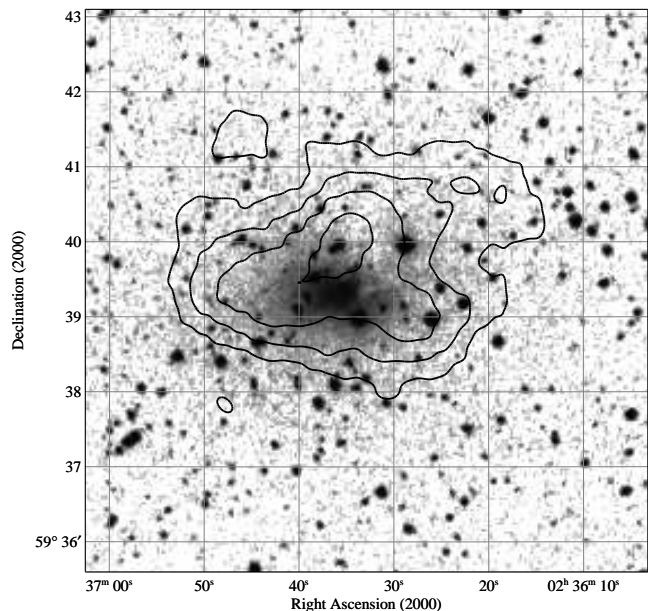There are several ways to explain the luminosity of

Figure 3. Red (*E*-band) POSS plate image of Mf1 overlaid with contours of the full-band GIS2 image. Contours correspond to 0.93, 0.74, 0.59 and 0.47 of the peak surface brightness. For comparison, the average background level is $\sim 10\,percent$ of the peak surface brightness with maximum fluctuations up to ~ 25 per cent of the peak surface brightness. The small apparent offset between the X-ray source and optical galaxy is interpreted as being due to positional uncertainty in the *ASCA* pointing (see discussion in the text). The source is significantly extended and appears inhomogeneous.

sources such as Dw1-X1 in terms of accreting compact objects. First, accretion onto a stellar black hole at a rate in excess of the Eddington limit would explain these sources. Strong magnetic fields may channel material onto the accreting object thereby allowing the Eddington limit to be breached by a factor few (e.g. A0538$-$66; Charles et al. 1983 and references therein). If Dw1-X1 does indeed contain a massive stellar black hole (with $M \sim 10 - 20\,\mathrm{M_\odot}$), only moderate super-Eddington accretion is required in order to explain the measured luminosity. However, there are many examples of more powerful ($L \gtrsim 10^{40}\,\mathrm{erg\,s^{-1}}$), but otherwise similar, sources in other nearby galaxies (Fabbiano 1995). To explain these as super-Eddington accretion onto such black holes would require the Eddington limit to be exceeded by a factor of 5–10. It is difficult to understand how such extreme super-Eddington accretion could occur in a stable way.

Secondly, these luminous sources may represent Eddington or sub-Eddington accretion onto a massive black hole (with $M \sim 100\,\mathrm{M_\odot}$ required in order to explain the most luminous examples). However, it is difficult to explain the formation of a $100\,\mathrm{M_\odot}$ non-nuclear black hole through the known processes of stellar evolution[†]. Of course, AGN are

---

[†] A black hole accreting at the Eddington luminosity with an efficiency of $\eta \sim 0.1$ will have a growth timescale of $\sim 10^8$ yrs. A binary system containing two massive stars will evolve (and presumably lose much of its mass) on a much more rapid timescale

thought to possess much more massive black holes: however, the formation of such supermassive black holes is likely to be intimately linked to their special location in the galaxy (e.g. see Rees 1984), and so probably will not provide a role model for the formation of non-nuclear massive black holes.

Finally, Dw1-X1 and similar luminous sources may be accreting stellar objects (either neutron stars or black holes) from which the emission is highly beamed. This possibility is discussed in more detail in Section 4.

3   MAFFEI 1

ASCA observed Mf1 on 1995 September 11/12 for approximately one day. Both SIS were used in 2-CCD mode (with the source positioned in chip 1 in SIS0 and chip 3 in SIS1). The data were cleaned and filtered as described in Section 2. The resulting good integration times are given in Table 1.

3.1   Image analysis

Images were extracted from the good data for each of the four instruments. Figure 3 shows contours of the GIS2 image overlaid on the POSS plate image of the Mf1 region. An X-ray source is clearly detected with an apparent offset of ~ 30 arcsec from the optical nucleus of Mf1. Given the positional accuracy of *ASCA* (Gotthelf 1995; also see Section 2.1), this is consistent with the source being centred on the optical galaxy (there is a 30 per cent probability of obtaining a 0.5 arcmin offset or more). Comparing Fig. 3 with the point source of Fig. 1 suggests that the Mf1 source has significant extent and substructure. In fact, both the hard-band image (> 2.5 keV) and soft-band image (< 2.5 keV) are *inconsistent* with the point spread function.

3.2   Spectral and temporal analysis of Maffei 1

Light curves and spectra were extracted for the counts contained within a circular region centred on the Mf1 source of radius 4 arcmins. Background spectra were extracted from source free regions of the same field of view for each detector. The count rates, 2–10 keV flux and 2–10 keV luminosity are reported in Table 1. There is marginal evidence for variability from the SIS light curves: the SIS light curves are inconsistent with a constant model at the 90 per cent level (χ^2/dof=41/31 and χ^2/dof=46/31 for constant model fits to SIS0 and SIS1 respectively). However, no clear variations are correlated between the two SIS instruments and no variability is evident in either GIS. Thus, we cannot confidently claim to have detected real variability.

Spectral fitting was performed as in Section 2.2, using background subtracted data from all four instruments simultaneously. The results of these fits are shown in Table 3. All models provide a satisfactory description of the data. Figure 4 shows the SIS0 and GIS2 spectra for Mf1 compared with the best fitting power-law spectrum.

($\sim 10^6$ yrs). Thus, it is difficult to understand how a stellar black hole (with an initial mass of $\sim 10\,M_\odot$) accreting at near the Eddington rate could be supplied with fuel for a sufficient length of time in order to grow to $\sim 100\,M_\odot$, unless the radiative efficiency is very low.
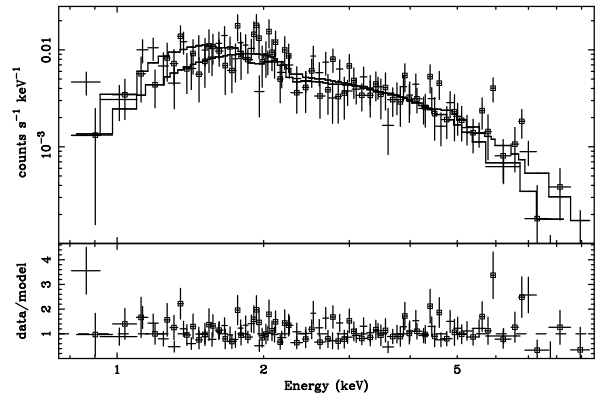

Figure 4. SIS0 (plain crosses) and GIS2 (crosses with open circles) spectra of the Maffei 1 emission. Although all four instruments were used for spectral fitting, only these two are displayed in order to maintain clarity. The top panel shows the data fitted with the best fit absorbed power-law model of Section 3.2 (shown by solid lines). The bottom panel illustrates the ratio of data to this best fit model.

3.3   The physical nature of the Maffei 1 emission

Probabilistic arguments identical to those presented in Section 2.3.1 lead us to conclude that the emission seen in this observation is intrinsic to Mf1. In fact, the probabilistic arguments are stronger in the case of Mf1 because the X-ray emission has a smaller angular separation from the optical nucleus. Given this conclusion, and the astrometric results of Markert & Donahue (1985), it is likely that the 0.5 arcmin offset of the centroid of the X-ray emission from the optical nucleus of the galaxy is purely due to astrometric error within the *ASCA* observation. Depending on the spectral model used, there is also spectral evidence for the Galactic absorption expected if this source were extragalactic (although spectral fitting with the black-body model can admit a rather lower cold column due to the intrinsic low-energy turnover of the black-body curve.)

To summarize the observed properties of the emission (given its identification with Mf1), it has a 0.5–10 keV luminosity of 2.5×10^{39} erg s^{-1} (assuming a power-law model) and a hard spectrum (well characterised by either a power-law with $\Gamma = 1.8^{+0.17}_{-0.15}$ or an optically-thin thermal model with $kT = 8.2^{+3.3}_{-2.0}$ keV) It is also spatially extended in both the hard and soft bands (with some suggestion of substructure within the image). [We do not consider the black-body model any further since it has no physical basis within the context of extended emission from elliptical galaxies.]

Given the high Galactic column density to this source, we must address the possibility that the observed extended structure is due to a Galactic dust scattering halo around an otherwise point source of emission (e.g. see Martin 1978). The process of X-ray scattering by dust is highly energy dependent (with scattering cross section varying roughly as E^{-2}, where E is the energy of the scattered photon). Thus the fact that both hard and soft band images are extended tends to rule out there being a significant dust halo. Additionally, Dw1-X1 has a similar line of sight Galactic column

Table 3. Spectral fitting results for the Mf1 source. Abbreviations are as follows: brems=thermal bremsstrahlung; rs=Raymond-Smith thermal plasma code (Raymond & Smith 1977); pl=power-law; NH=cold absorbing column. All errors are quoted at the 90 per cent confidence level for one interesting parameter, $\Delta\chi^2 = 2.7$.

Model	parameter	value	χ^2/dof
bb+NH	temperature	$kT = 1.06^{+0.04}_{-0.05}$ keV	264/256
	cold absorbing column	$N_{\mathrm{H}} < 8.5 \times 10^{21}$ cm^{-2}	
brems+NH	temperature	$kT = 8.2^{+3.3}_{-2.0}$ keV	256/256
	cold absorbing column	$N_{\mathrm{H}} = 8.5^{+1.6}_{-1.4} \times 10^{21}$ cm^{-2}	
rs+NH	temperature	$kT = 8.5^{+3.3}_{-2.0}$ keV	256/255
	abundance	$Z < 0.22$	
	cold absorbing column	$N_{\mathrm{H}} = 8.5^{+1.6}_{-1.4} \times 10^{21}$ cm^{-2}	
pl+NH	photon index	$\Gamma = 1.80^{+0.17}_{-0.15}$	262/256
	cold absorbing column	$N_{\mathrm{H}} = (1.0 \pm 0.2) \times 10^{22}$ cm^{-2}	

yet displays a pointlike source of emission. We conclude that the effects of Galactic X-ray dust scattering on the observed extent of the Mf1 emission is negligible.

This combination of properties places severe constraints on possible explanations of this emission. The imaging data alone might be interpreted as evidence for emission from an extended hot ISM. However, our spectral data discounts this possibility in the following manner. A hot ISM would produce thermal emission at the virial temperature of the galaxy, $kT \approx 1$ keV. The observed spectrum is too hard for it to be dominated by such a component. In fact, adding such a component to either the power-law or thermal model continuum models allows an upper limit to be placed on the ISM emission (assuming it to be at 1 keV and not to suffer intrinsic absorption): the resulting upper limit on the 0.5–10 keV luminosity of the ISM (at the 90 per cent confidence level for one interesting parameter, $\Delta\chi^2 = 2.7$) is 1.4×10^{38} erg s^{-1}. Thus, the spectral constraints require such ISM emission to be less than 5 per cent of the total *ASCA* band flux. This upper limit on the ISM emission is low for a typical elliptical galaxy. A contributing factor may be the restricted region (corresponding to a radius of 3 kpc at the distance of Mf1) that we choose for our analysis: there could be a more spatially extended soft component which is undetectable above the background due to Galactic absorption. Also, the upper limit is much less restrictive if a cooler ISM is considered since most of the thermal ISM flux is then at energies which are almost completely absorbed by the line of sight cold material. Assuming a temperature of $kT = 0.5$ keV, the upper limit on the 0.5–10 keV luminosity becomes 2.2×10^{39} erg s^{-1}. Note that if such a soft component was indeed present, a significantly larger absorbing column than that reported in Table 3 would be necessary.

The extended and hard nature of the source suggests that the emission is from a number of accreting compact objects. Similar hard emission has been found in other elliptical galaxies (Canizares, Fabbiano & Trinchieri 1987; Matsushita et al. 1994). There are two obvious possibilities to explain this emission. First, the emission may be due to a large number of low-mass X-ray binaries (LMXB). Assuming a typical LMXB 2–10 keV luminosity of $\sim 10^{37}$ erg s^{-1}, approximately 100 such systems are required to provide all of the observed emission. Secondly, a large portion of the

emission may be due to a small number of luminous systems, similar to Dw1-X1. There may also be a contribution from a LLAGN. Note that the spectra of LLAGN, a population of LMXB and luminous compact objects are similar (Makishima et al. 1989). Thus, it is difficult to distinguish between these various explanations on spectral grounds alone.

In order to make further progress with the study of the Mf1 emission, high resolution X-ray imaging data of Mf1 is required in order to investigate any substructure within the emission and, if possible, resolve individual luminous sources. Variability, or lack thereof, is also an important diagnostic that should be addressed in future observations. We are engaged in a programme to make such observations.

4   BEAMED SOURCES AND GALACTIC SUPERLUMINALS

X-ray sources producing $\sim 10^{40}$ erg s^{-1} appear to be relatively common in nearby galaxies (Fabbiano 1995; Marston et al. 1995). The available numbers indicate a mean of approximately one such source per galaxy. One candidate class of objects that we propose here encompasses the Galactic superluminals such as GRS 1915+105 and GRO J1655−40 (Mirabel & Rodriguez 1995; Mirabel & Rodriguez 1994; Harmon et al. 1995; Hjellming & Rupen 1995). These objects are strong, sometimes transient, X-ray sources which have radio jets showing superluminal motion. There is also a class of non-transient Galactic sources (e.g. 1E 1740.7-2942; Mirabel et al. 1992) with jets which have yet to show superluminal motion. The velocity of the jets in the superluminal objects is close to 0.92c. Neither of these objects has an X-ray luminosity much exceeding 10^{38} erg s^{-1}, *but this could be exceeded if we were to view the object down the jet.*

Given a jet velocity of 0.92c the corresponding Lorentz factor is $\gamma \sim 3$, so the jet emission is beamed into a solid angle of $\gamma^{-2} \sim 0.1$ sr. Thus the apparent luminosity could be $2\pi\gamma^2 \sim 60$ times higher along that direction than the actual power of the jet (allowing for symmetric twin jets). If the jet has a luminosity of $L \sim 10^{38}$ erg s^{-1} (comparable to the Eddington limit for 1 M$_\odot$), the object could appear to have a luminosity of $2\pi\gamma^2 L \sim 6 \times 10^{39}$ erg s^{-1} if viewed within 20° of its jet. Of course the jet could be more powerful (as

indicated for GRS 1915+105; Mirabel & Rodriguez 1995) and the efficiency for the conversion of jet power into X-ray flux, presumably via shocks, is unknown. We note that this process in blazars may be highly efficient and a hard power-law X-ray spectrum is produced.

Theoretical models of relativistic jets have been developed in the context of radio-loud AGN (see review by Sikora 1994 and references within). In the most simple models, the jet radiation is synchrotron emission from relativistic electrons gyrating in the magnetic field of the jet plasma. Self-absorption and synchrotron self-Compton processes are known to be important for understanding the observed spectrum. In addition, pair-production may be influential in determining the γ-ray emission at the base of the jet. It is not clear how well these models for AGN jets will describe jets in Galactic superluminal sources. It is unlikely that a simple scaling of the spectrum of a beamed AGN (e.g. a blasar) will successfully describe the spectrum of such a source. Thus, significant theoretical work is required in order to make predictions for the full-band spectrum of a beamed Galactic superluminal-type source.

One prediction we can make is that non-thermal continuum emission would dominate at all wavelengths. Thus, spectral features, such as the fluorescent iron Kα emission line expected from the accretion disk, would be very weak. This analogy with blazars might also suggest that these objects should display extremely rapid variability. Future observations with the next generation of imaging X-ray observatories (with larger collecting area) will be able to address these issues.

The statistics for such a scheme appear to be acceptable. The two known Galactic superluminal objects have inclinations to our line of sight of $\sim 70°$ and $\sim 85°$. Assuming that the Galactic superluminal sources are randomly oriented, the fact that we see a source as close to the plane of the sky as 85° suggests there could be at least ~ 10 such sources within our Galaxy and some selection effect could be picking out sources with high inclinations[‡]. If there are ~ 10 or more such objects per galaxy, the probability that an observer lies within the beaming cone (taken to have a half angle of $\gamma^{-1} \sim 20°$) of one of these sources for a given galaxy can exceed 0.2. Although the transient nature of the Galactic superluminal sources will reduce this probability, the existence of a steady class of jetted sources may offset this effect. Thus, if other galaxies harbour similar populations of beamed sources then many of the luminous objects seen can be accounted for.

5   CONCLUSIONS

ASCA clearly detects X-ray emission from the nearby galaxies Dw1 and Mf1. The degree of absorption seen in the X-ray

---

[‡] Galactic superluminal sources alert us to their presence by their X-ray transient behaviour. If the X-ray emission from such a transient event was preferentially directed perpendicularly to the jet axis (i.e. in the plane of the putative accretion disk), this would produce the required selection effect. Note that this disk-plane emission need not be directly related to the beamed (jet) X-ray emission.

spectra of these two emissions, as well as probabilistic arguments, lead us to believe that the emission is intrinsic to the galaxy in both cases.

The Dw1 emission, Dw1-X1, is consistent with being from a point source with a 0.5–10 keV luminosity of $1.4 \times 10^{39} \, \mathrm{erg \, s^{-1}}$ at the distance of Dw1. It has a hard spectrum well described by a power-law of photon index $\Gamma = 2.0$ absorbed by a column density $N_{\mathrm{H}} \sim 1.4 \times 10^{22} \, \mathrm{cm^{-2}}$ of cold material. The apparent 3 arcmin offset (corresponding to 2.6 kpc at the distance of Dw1) of Dw1-X1 from the optical nucleus cannot be reasonably explained by pointing inaccuracies. Thus Dw1-X1 appears to be either a luminous non-nuclear accreting X-ray source of the type found in many other nearby galaxies, or a X-ray bright supernova remnant similar to SN1978K in NGC 1313. No variability is seen, although variability would have to be dramatic in order to be detectable in such a faint source. No nuclear emission is seen from Dw1: the corresponding limit on the 2–10 keV flux of the nucleus is $F_{2-10} \lesssim 1 \times 10^{-13} \, \mathrm{erg \, cm^{-2} \, s^{-1}}$.

In contrast, the Mf1 emission is not pointlike. Both the hard and soft band images clearly show extension beyond the point spread function. The overall spectrum is hard and well described by a power-law with $\Gamma = 1.8$ modified by absorption from a cold column density of $N_{\mathrm{H}} \sim 1 \times 10^{22} \, \mathrm{cm^{-2}}$. The spectral data rule out the possibility that any significant part of the observed emission originates from thermal ($kT \sim 1 \, \mathrm{keV}$) ISM emission: an upper limit on the 0.5–10 keV luminosity of any such thermal component is $1.4 \times 10^{38} \, \mathrm{erg \, s^{-1}}$ (which is 5 per cent of the total observed X-ray emission). We interpret this emission as being from a number of accreting stellar systems. We cannot distinguish between a small number of luminous sources (each with a 0.5–10 keV luminosity of $\sim 10^{39} \, \mathrm{erg \, s^{-1}}$) or a large number of ordinary LMXB. There might also be a LLAGN present. Further progress requires high spatial resolution X-ray observations.

Prompted by our results on Dw1-X1, we discuss the physical nature of non-nuclear sources with luminosities up to $\sim 10^{40} \, \mathrm{erg \, s^{-1}}$. Many such sources are now known with an average of about one per galaxy. Given the compact and variable nature of these sources, it is tempting to identify them as hyper-luminous XRB. In particular, we discuss a possible connection between such sources and Galactic superluminal objects. The complexities of realistic relativistic jet models make detailed predictions difficult, but we have demonstrated that this hypothesis is feasible on energetic grounds.

REFERENCES

Almaini O., Shanks T., Boyle B. J., Griffiths R. E., Roche N., Stewart G. C., Georgantopoulos I., 1996, MNRAS, in press

Brandt, W. N., Halpern J. P., Iwasawa K., 1996, MNRAS, in press

Boyle B. J., Shanks T., Georgantopoulos I., Stewart G. C., Griffiths R. E., 1994, MNRAS, 271, 639

Bregman J. N., Cox C. V., Tomisaka K., 1993, ApJ, 415, L79

Burton W. B., Verheijen M. A. W., Kraan-Korteweg R. C., Henning P. A., 1996, A&A, 309, 687

Buta R. J., McCall M. L., 1983, 205, 131

Canizares C. R., Fabbiano G., Trinchieri G., 1987, ApJ, 312, 503

Charles P. A. et al., 1983, MNRAS, 202, 657

Colbert E., Petre R., Schlegel E. M., Ryder S. D., 1995, ApJ, 446, 177

Ehle M., Pietsch W., Beck R., 1995, A&A 295, 289

Fabbiano G., 1995, in Lewin W. H. G., van Paradijs J., van den Heuvel E. P. J., eds, X-ray binaries, Cambridge University Press, Cambridge, p390

Fabbiano G., Trinchieri G., 1987, ApJ, 315, 46

Fabian A. C., Terlevich R., 1996, MNRAS, submitted

Fabian A. C., Ward M. J., 1993, MNRAS, 263, L51

Green D. A., 1989, A&A, 78, 277

Gotthelf E. V., 1996, *ASCA* News, 4, 310

Harmon A. et al., 1995, Nat, 374, 703

Hertz P., Grindlay J. E., 1984, ApJ, 278, 137

Hjellming R. M., Rupen M. P., 1995, Nat, 375, 464

Ishisaki Y. et al., 1996, PASJ, 48, 237

Kraan-Korteweg R.C., Loan A.J., Burton W.B., Lahav O., Fergusson H.C., Henning P.A., Lynden-Bell D., 1994, Nat, 372, 77

Loan A.J. et al., 1996, MNRAS, 280, 537

Maffei P., 1968, PASP, 80, 618

Makishima K., 1994, in Makino F., Ohashi T., eds, New Horizon of X-ray Astronomy, Universal Academy Press, Tokyo, p171

Makishima K., Ohasi T., Hayashida K., Inoue H., Koyama K., 1989, PASJ, 41, 697

Makishima K. et al. 1994, PASJ, 46, L77

Markert T. H., Donahue M. E., 1985, ApJ, 297, 564

Marston A. P., Elmegreen D., Elmegreen B., Forman W., Jones C., Flanagan K., 1995, ApJ, 438, 663

Martin P. G., 1978, Cosmic Dust, Oxford University Press, p67

Matsushita K. et al., 1994, ApJL, 436, 41

Mirabel I. F., Rodriguez L. F., 1994, Nat, 371, 46

Mirabel I. F., Rodriguez L. F., 1995, in Bohringer H., Morfill G. E., Trumper J. E., eds, Seventeenth Texas Symposium on Relativistic Astrophysics and Cosmology, New York Academy of Sciences, New York, p21

Mirabel I. F., Rodriguez L. F, Cordier L. F., Paul J., Lebrum F., 1992, Nat, 358, 215

Okada K. et al., 1994, in Makino F., Ohashi T., eds, New Horizon of X-ray Astronomy, Universal Academy Press, Tokyo, p515

Petre R., Mushotzky R. F., Serlemitsos P. J., Jahoda K., Marshall F. E., 1993, ApJ, 418, 644

Petre R., Okada K., Mihara T., Makishima K., Colbert E. J. M. 1994, PASJ, 46, L115

Rees M. J. , 1984, ARAA, 22, 471

Ryder S., Staveley-Smith L., Dopita M., Robert P., Colbert E., Malin D., Schlegel E., 1993, ApJ, 416, 167

Schegel E. M., 1995, Rep. Prog. Phys., 58, 1375

Sikora M., 1994, ApJS, 90, 923

Stocke J. T., Wurtz R., Kühr H., 1991, AJ, 102, 1724

Takano M., Mitsuda K., Fukazawa Y., Nagase F., 1994, ApJ, 436, L47

Tanaka Y., Inoue H., Holt S. S., 1994, PASJ, 46, L37

Timmes F. X., Woosley S. E., Weaver T. A., 1996, ApJ, 457, 834

Van den Bergh S., 1994, AJ, 107, 1328

Van Dyk S., Weiler K., Sramek R. A., Panagia N., 1990, ApJ, 419, L69

Voges W. et al., 1996, A&A, in press

Weiler K. W., Panagia N., Sramek R. A., 1990, ApJ, 364, 611